

A LOW-PROFILE HIGH-VOLTAGE COMPACT GAS SWITCH^{*1}

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Abstract

This paper discusses the development and testing of a low-profile, high-voltage, spark-gap switch designed to be closely coupled with other components into an integrated high-energy pulsed-power source. The switch is designed to operate at 100 kV using SF₆ gas pressurized to less than 0.7 MPa. The volume of the switch cavity region is less than 1.5 cm³, and the field stress along the gas-dielectric interface is as high as 130 kV/cm. The dielectric switch body has a low profile that is only 1-cm tall at its greatest extent and nominally 2-mm thick over most of its area. This design achieves a very low inductance of less than 5 nH, but results in field stresses exceeding 500 kV/cm in the dielectric material. Field modeling was done to determine the appropriate shape for the highly stressed insulator and electrodes, and special manufacturing techniques were employed to mitigate the usual mechanisms that induce breakdown and failure in solid dielectrics. Static breakdown tests verified that the switch operates satisfactorily at 100 kV levels. The unit has been characterized with different shaped electrodes having nominal gap spacings of 2.0, 2.5, and 3.0 mm. The relationship between self-break voltage and operating pressure agrees well with published data on gas properties, accounting for the field enhancements of the electrode shapes being used. Capacitor discharge tests in a low inductance test fixture exhibited peak currents up to 25 kA with characteristic frequencies of the ringdown circuit ranging from 10 to 20 MHz. The ringdown waveforms and scaling of measured parameters agree well with circuit modeling of the switch and test fixture. Repetitive operation has been demonstrated at moderate rep-rates up to 15 Hz, limited by the power supply being used. Preliminary tests to evaluate lifetime of the compact switch assembly have been encouraging. In one case, after more than 7,000 high-current ringdown tests with approximately 30 C of total charge transferred, the switch continued to operate satisfactorily with no apparent tracking or deterioration of the insulator.

Introduction

Spark gap switches are commonly used in trigger generators, pulse forming networks, Marx generators, and other high-energy pulsed-power systems. They are particularly well suited for applications that require switching of very high voltages and rather high currents.

Marx-type high-voltage generators most frequently use spark gap switches. In principle, Marx generators are simple, and their performance is mainly determined by the basic capacitors and switches that make up each stage. In most applications, Marx generators are constructed with standard, commercially available components that are arranged in an orderly manner into compact assemblies. Since these components are made for general use, their packaging and terminal styles are usually less than optimal for achieving maximum performance and the compactness needed for some applications. Significant improvements can be realized by modifying standard components or by manufacturing special components to fit into integrated packages.

We have developed a design for a repetitively-switched, Marx-type high-voltage generator based on custom components that can be closely coupled and integrated into an extremely compact assembly.¹ This ultra-compact Marx (UCM) can be used in a variety of special

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14. ABSTRACT

This paper discusses the development and testing of a low-profile, high-voltage, spark-gap switch designed to be closely coupled with other components into an integrated high-energy pulsed-power source. The switch is designed to operate at 100 kV using SF₆ gas pressurized to less than 0.7 MPa. The volume of the switch cavity region is less than 1.5 cm³, and the field stress along the gas-dielectric interface is as high as 130 kV/cm. The dielectric switch body has a low profile that is only 1-cm tall at its greatest extent and nominally 2-mm thick over most of its area. This design achieves a very low inductance of less than 5 nH, but results in field stresses exceeding 500 kV/cm in the dielectric material. Field modeling was done to determine the appropriate shape for the highly stressed insulator and electrodes, and special manufacturing techniques were employed to mitigate the usual mechanisms that induce breakdown and failure in solid dielectrics. Static breakdown tests verified that the switch operates satisfactorily at 100 kV levels. The unit has been characterized with different shaped electrodes having nominal gap spacings of 2.0, 2.5, and 3.0 mm. The relationship between self-break voltage and operating pressure agrees well with published data on gas properties, accounting for the field enhancements of the electrode shapes being used. Capacitor discharge tests in a low inductance test fixture exhibited peak currents up to 25 kA with characteristic frequencies of the ringdown circuit ranging from 10 to 20 MHz. The ringdown waveforms and scaling of measured parameters agree well with circuit modeling of the switch and test fixture. Repetitive operation has been demonstrated at moderate rep-rates up to 15 Hz, limited by the power supply being used. Preliminary tests to evaluate lifetime of the compact switch assembly have been encouraging. In one case, after more than 7,000 high-current ringdown tests with approximately 30 C of total charge transferred, the switch continued to operate satisfactorily with no apparent tracking or deterioration of the insulator.

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applications requiring a compact high-voltage pulsed-power source. The concept relies on a low-profile, low-inductance, high-voltage, spark-gap switch.

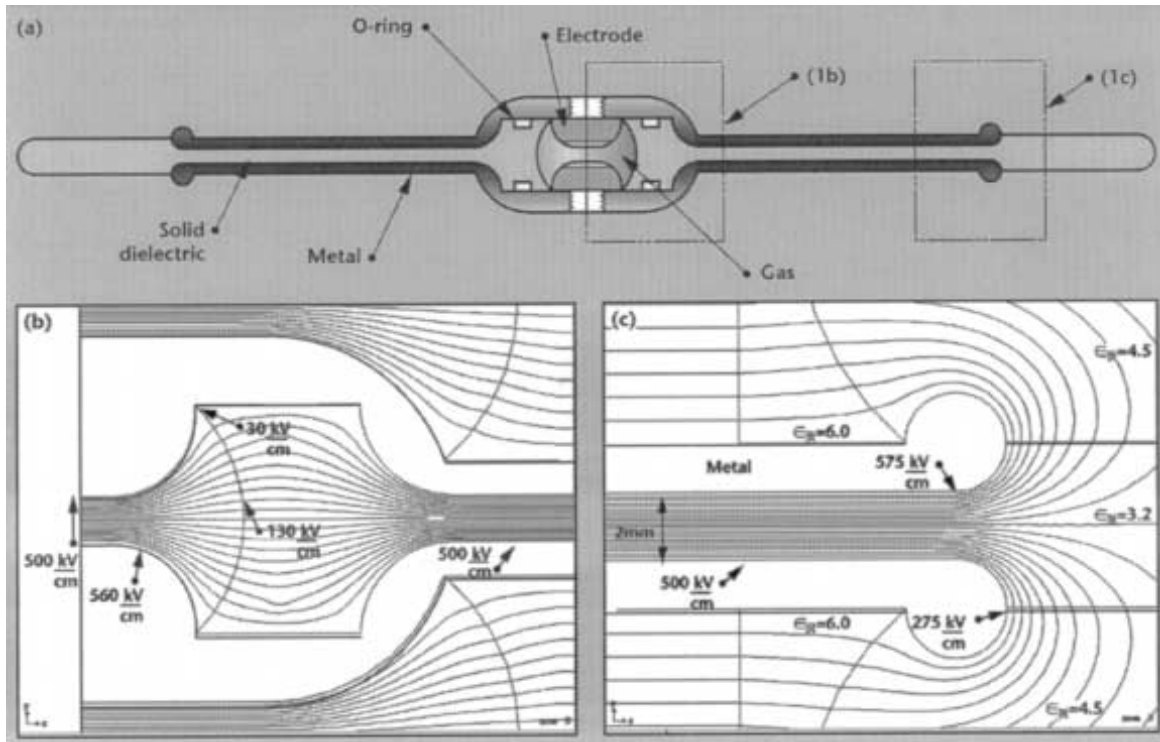


Figure 1. (a) Schematic of compact gas switch; (b) and (c) show field modeling results.

Switch Design

We evaluated many design options and performed field modeling to evaluate the electrical stresses and quantify field enhancements of different shaped assemblies. Through an iterative process, we identified the limiting features and devised suitable design and construction methods to satisfy the basic requirements. Figure 1a is a sketch of the compact gas switch.

The shape of the metallic and dielectric parts is crucial to properly manage the electric fields and keep the stresses below the threshold for flashover or breakdown of a material. Figures 1b and 1c show field modeling results where contours of equipotential lines are plotted. The metal electrodes and insulator surfaces have been appropriately shaped to reduce electric field stresses in the weakest regions where dissimilar materials meet, and to spread the fields evenly throughout the dielectric materials, allowing them to operate closer to their intrinsic breakdown levels.

Figure 1b shows that for the chosen dimensions with an applied voltage of 100 kV, the electric field is less than 30 kV/cm at the triple-point region, and is less than 130 kV/cm along the envelope of plastic material containing the pressurized gas. These stress levels are below the thresholds reported by others as troublesome.^{2,3} The average field across the thinnest annular region of plastic is 500 kV/cm, whereas the highest field at the outermost field-enhanced region is 575 kV/cm.

The gap between the cathode and anode electrodes is sized according to the desired operating level and gas pressure for a particular gas species or mixture. A nominal gap of 2.0 mm will normally break down at 100 kV with SF₆ pressurized to 100 psia. Field modeling allowed us to correct the empirical relationship for gas breakdown of planar gaps by including the effect of field enhancement at the edges. As evident in Fig. 1b, the fields are enhanced along the radiused edge of the switch electrodes, reaching 560 kV/cm. This results in an enhancement factor (f^*) of 1.120, given by the ratio of 560 kV/cm to 500 kV/cm.⁴

Test Apparatus

We constructed a special test fixture to evaluate various switches and demonstrate their performance over the desired range of operating parameters.

Figure 2 is a photograph of the assembled unit. The slotted metal cylinder is the outer current return path for performing current ringdown tests. The finned cylindrical structure below the test fixture is a high-energy current-viewing resistor used as a diagnostic. Figure 3 is a photograph of the components to be evaluated before assembly inside the test fixture. The photo shows a 2-mm-thick switch body nestled between two surrogate annular capacitors. The portion of the switch body that can be seen is 5-mm thick and extends about 2.0 cm beyond the outer radius of the capacitor electrodes. The capacitor assemblies are constructed of eight ceramic capacitors mounted in a ring around a gas sealed cylindrical insulator.

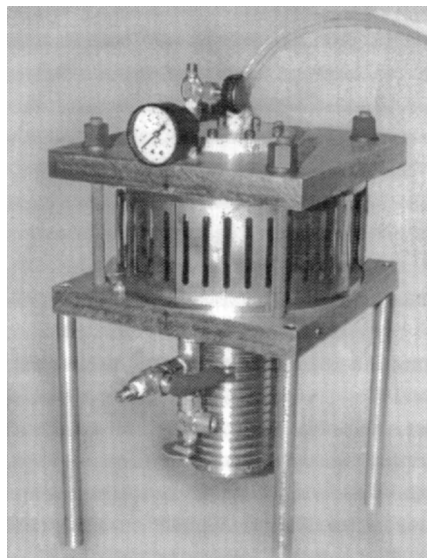


Figure 2. Photograph of test fixture

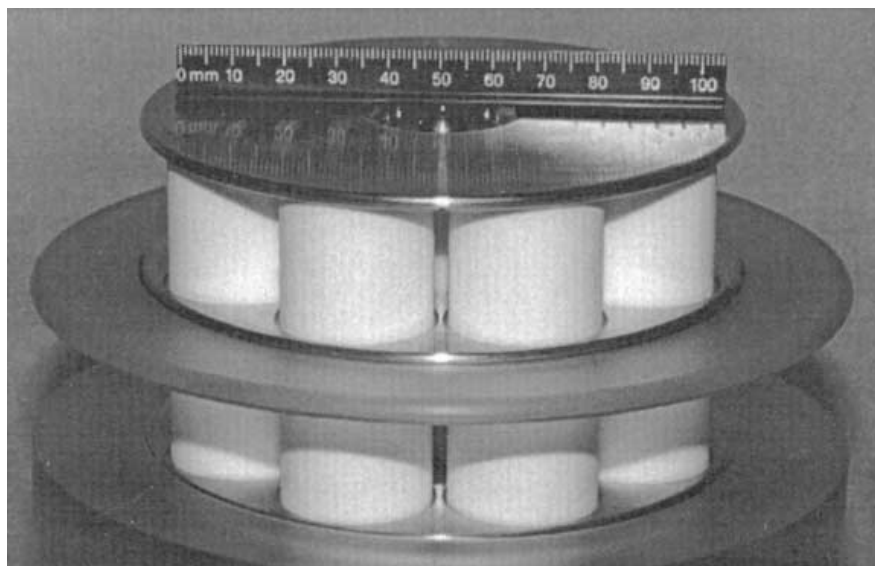


Figure 3. Photograph of compact gas switch nestled between two capacitor assemblies.

Test Results

Static breakdown tests were performed first to observe the relationship between self-break voltage and operating pressure. Three different sets of electrodes were used to characterize the compact gas switch with nominal gap spacings of 2.0, 2.5, and 3.0 mm. Figure 4 shows results from self-break operation for the 2.5-mm gap with SF_6 gas. The triangular-shaped markers represent the breakdown measurements that were made at each pressure increment of 5 psi. The open circles and curve fit represent the well-known relationship for breakdown of SF_6 gas⁴ accounting for the field enhancements for these particular shaped electrodes.

While there is some statistical variation in the breakdown levels, the general agreement with the empirical model indicates that the switch indeed functions as intended. Considerable testing confirmed that the electric field stress has been properly managed at the triple points and along the insulator surface, and that the switch operates satisfactorily at 100 kV levels.

Further testing was done to exercise the compact gas switch at desired peak currents and charge-transfer levels. Figure 5 shows the current trace from a typical ringdown event. The peak current of 20 kA is limited mainly by the rather large inductance of the test fixture and capacitors. Subsequent testing with a somewhat lower inductance circuit achieved peak currents as high as 25 kA. Figure 6 shows the relationship between peak current and the switch operating voltage. The solid square markers indicate the experimental data points. The open triangular markers and solid curve fit represent analytical estimates of the peak current based on circuit parameters assuming ideal capacitors.

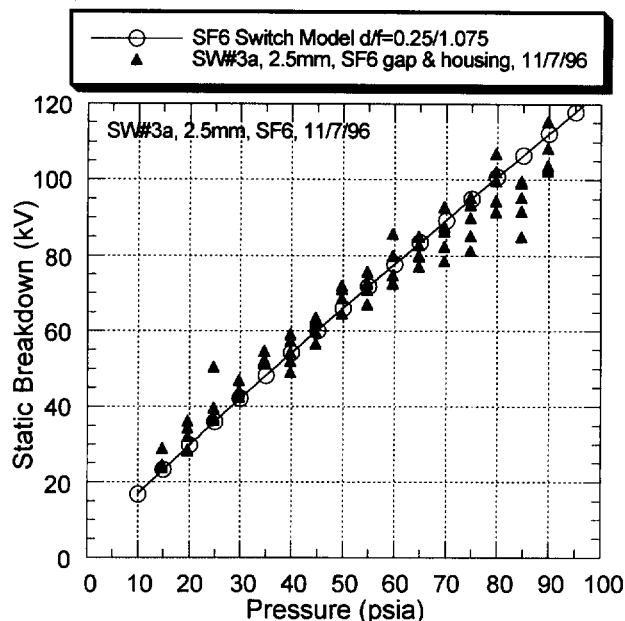


Figure 4. Static breakdown test results

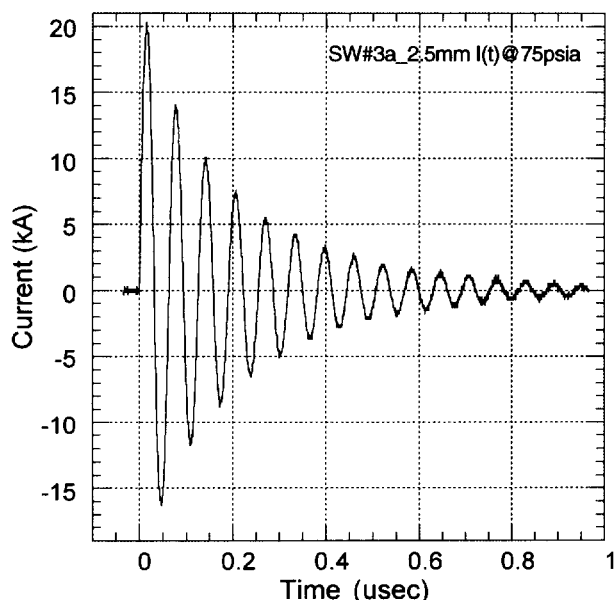


Figure 5. Current waveform from ringdown event

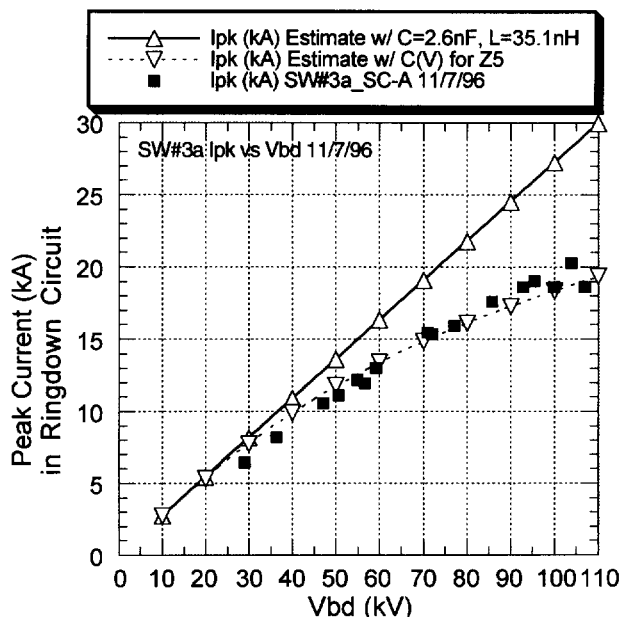


Figure 6. Peak current verses operating voltage

The dashed curve fit in Figure 6 represents the analytical estimates of peak currents using actual values for the capacitors knowing their voltage dependent characteristics. The capacitance of the Z5 ceramic capacitors used in these initial tests is known to fall off severely at higher voltage levels. We performed LCR-bridge measurements at elevated levels to accurately characterize these capacitors.⁵

Next, we performed tests to determine whether the insulator would survive repetitive high-energy pulses, or whether electrode erosion would become troublesome. Figure 7 shows a typical voltage trace from a 4-second burst-mode operation of a 3-mm gap switch with SF₆ at

65 psia and the 100-kV power supply current limited by a 20-M Ω series resistor. Considerable testing was done at these moderate rep-rates of 10 to 15 Hz. We anticipate the compact switch will operate satisfactorily at rep-rates up to 50 Hz. This mode of operation was also used to determine the statistical variation of voltage breakdown levels to evaluate how well the switch would function in a Marx-type high-voltage generator.

For the 4-s burst shown in Figure 7, the mean operating voltage was 88.8 kV and the standard deviation was 4.5 kV or 5.0%. This statistical variation is adequate for a Marx generator to function reliably with a reasonable amount of voltage coupling between stages to ensure successive switch operation.

To evaluate the expected lifetime of such a compact switch assembly, multiple 4-s bursts were taken, and the voltage and ringdown current waveforms were recorded for each shot. The switch still operated satisfactorily after more than 175 bursts, totaling more than 7,000 individual shots. This series of tests ended when one of the capacitors failed.

Figure 8 shows a close-up photograph of the Lexan switch housing. No tracking or deterioration could be seen. After inspection, the switch was reinstalled for further testing.

Most of the electrical testing was done with a polycarbonate material (Lexan). Figure 9 shows a close-up photograph of one switch housing made from an extruded Lexan cylinder. Stress fractures were apparent after machining the inner switch cavity. This particular switch still operated satisfactorily for more than 1,000 shots; however, the crazing became progressively worse.

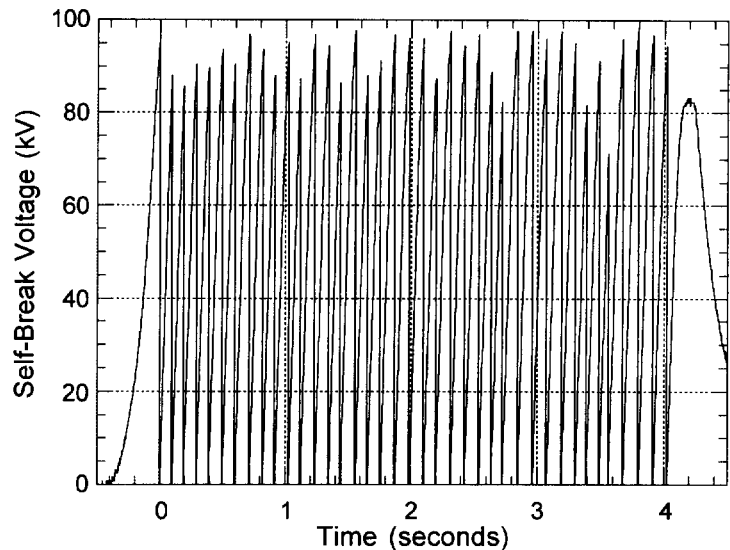


Figure 7. Voltage trace from repetitive operation

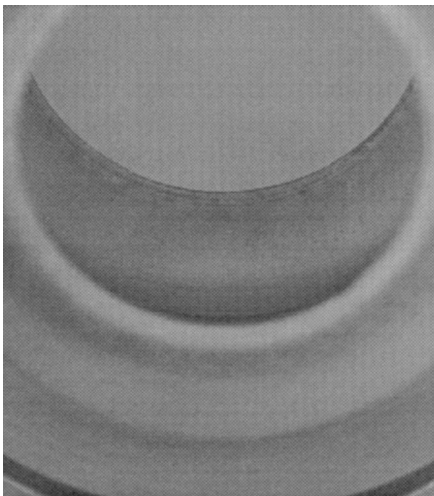


Figure 8. Photo of tested Lexan switch housing with 1-cm electrode opening

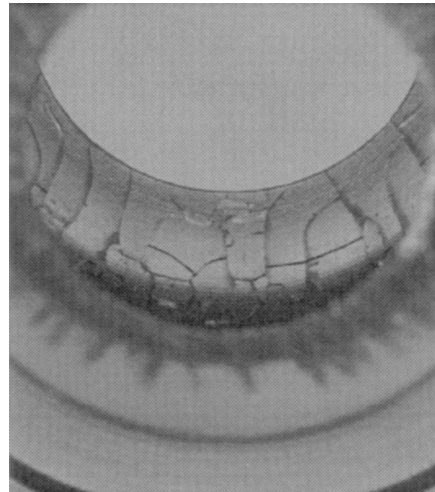


Figure 9. Photo of machined Lexan switch housing with stress fractures

Several types of insulator materials were used to evaluate machining methods. Switch housings were also manufactured using alumina-trihydrate (ATH) loaded epoxy and EPON-825 thermoset resin. ATH machined very easily, whereas some difficulty was experienced machining the EPON material.

Some information about electrode erosion was gained from these tests. The replaceable button electrodes were weighed before and after the lifetime tests described above. The mass loss was 5.4 mg for each of the cathode and anode electrodes, and the erosion appeared uniformly distributed over the front face of the electrodes as shown in Figure 10. The total charge transferred through the switch during the period in which these electrodes were installed was 30.4 C. The specific mass loss

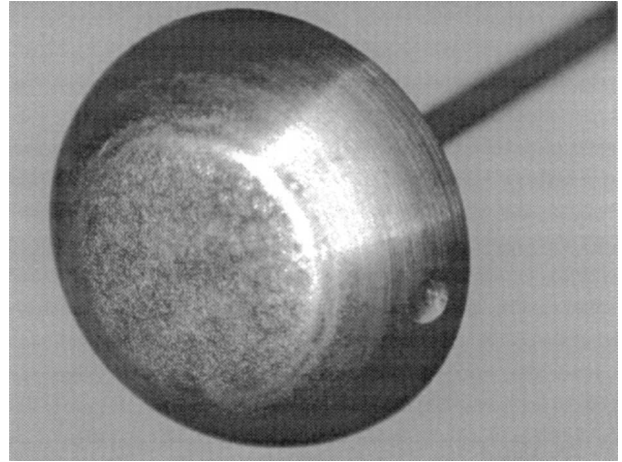


Figure 10. Photograph of button electrode

amounted to 0.178 mg/C, which is consistent with typical erosion rates reported in the literature.⁶

Summary

We have developed a low-profile, high-voltage, spark-gap switch designed to be closely coupled with other components into an integrated high-energy pulsed-power source. We performed field modeling to determine the appropriate shape for the highly stressed insulator and electrodes, and employed special manufacturing techniques to mitigate the usual mechanisms that induce breakdown and failure in solid dielectrics⁷. We have constructed and tested a prototype switch unit and achieved satisfactory operation at 100 kV levels. Preliminary tests to evaluate repetitive operation and lifetime have been encouraging.

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